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# Exergetic life cycle assessment of a grid-connected, polycrystalline silicon photovoltaic system

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**Abstract**

*Purpose* Nowadays, the intensive use of natural resources in order to satisfy the increasing energy demand suggests a threat to the implementation of the principles of sustainable development. The present study attempts to approach thermodynamically the depletion of natural resources in the methodological framework and the principles of life cycle assessment (LCA).

*Methods* An environmental decision support tool is studied, the exergetic life cycle assessment (ELCA). It arises from the convergence of the LCA and exergy analysis (EA) methodologies and attempts to identify the exergetic parameters that are related to the life cycle of the examined system or process. The ELCA methodology, beside the fact that it locates the system parts which involve greater exergy losses, examines the depletion of natural resources (biotic and abiotic) and the sustainable prospective of the examined system or process, under the scope of exergy. In order to obtain concrete results, the ELCA methodology is applied to a large-scale, grid-connected, photovoltaic (PV) system with energy storage that is designed to entirely electrify the Greek island of Nisyros.

*Results and discussion* Four discerned cases were studied that reflect the present state and the future development of the PV technology. The exergy flows and balance for the life cycle of the PV system, as they were formed in the ELCA study, showed that the incoming exergy (solar radiation, energy sources, and materials) is not efficiently utilized. The greater exergy losses appear at the stage of the operation of the PV installation. Due to the fact that contribution of the renewable exergy (solar radiation) to the formation of the total incoming exergy of Life Cycle is significant, it emerges that satisfaction of electric power needs with a PV system appears to be exergetic sustainable. The increase of the Life Cycle exergetic efficiency supported by the future technological scenario in contrast to present scenarios emerges from the increased electricity output of the PV system. Consequently, the increased exergetic efficiency involves decreased irreversibility (exergy losses) of the PV system's life cycle.

*Conclusions* The application of ELCA in electricity production technologies exceeds the proven sustainable prospective of the PV systems; however, it aims to show the essence of the application of ELCA methodology in the environmental decision making process. ELCA can be a useful tool for the support and formation of the environmental decision making that can illustrate in terms of exergetic sustainability the examined energy system or process.

**Keywords** Exergetic efficiency · Exergetic life cycle assessment · Poly-silicon Photovoltaic system

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## 1 Introduction

During the previous decades, the world energy demand has shown a rapid increase. Energy consumption is projected to keep growing by 56 % between 2010 and 2040 reaching a total consumption in various forms of energy of 820 quadrillion BTU in 2040 (Energy Information Administration 2013; Wolfram et al. 2012). Most of the growth in energy consumption will occur in the developing world, with a forecasted increase of 90 %, in contrast to a small increase of 17 % in

the developed world by 2040 (Energy Information Administration 2013). In every part of the world, economic growth is strongly related to secure and sufficient energy reserves (Kruyt et al. 2009). Due to their relatively low cost, fossil fuels have been extensively used in order to satisfy the increasing energy demand (Lior 2008; Asif and Muneer 2007). However, existing energy production technologies and corresponding applied energy policies accelerate the degradation of the natural environment (Omer 2008). More specifically, processes that are related to energy production, from stage of raw material extraction to that of providing energy services, cause impacts on human health and ecosystems (von Blottnitz and Curran 2007; Vitousek et al. 1997). Consequently, the future energy policy should aim for the preservation of the natural resources (natural capital) and the minimization of the environmental impacts caused by human activities (Glavič and Lukman 2007; Omer 2008). The main objective should be the implementation of practices and policies that render in the long-term the global energy balance economically, socially, and environmentally sustainable (Midilli et al. 2006; Doran 2002).

Sustainable development is defined as the development that meets the needs of the present without compromising the ability of future generations to meet their own needs, thus integrating economic, environmental, and social imperatives in a balanced way (Van Marrewijk 2003; Dahlsrud 2008; Dincer 2000; Struble and Godfrey 2004). The use of natural resources for satisfying energy demands is responsible for several environmental impacts (Mont 2002; Hinterberger et al. 1997). The essence of sustainable development incorporates in the long-term environmental parameters into the formation of energy policy (Boulanger and Bréchet 2005). For the last 20 years, the European Union has put in use various tools and models that led to European and international agreements on harmonized emission control strategies (Amann et al. 2011). The Regional Air Pollution Information and Simulation (RAINS) model has been used as the basic platform for the environmental negotiations in Europe, and in specific, to quantify the obligations in its 1999 Directive on National Emission Ceilings (Amann and Lutz 2000) as well as the ASAM and the MERLIN models in a supplementary manner (Oxley and ApSimon 2007; Reis et al. 2005). In 2009, the Convention of Long-Range Transboundary Air Pollution proceeded with supporting a Europe-wide harmonized strategy for further mitigating greenhouse gasses in the atmosphere. This has been attempted through the GAINS model that helps focusing environmental strategies on issues such as desired levels of environmental quality and the willingness to support financially the relevant goals set by policy makers (Amann et al. 2011). Apart from those models, some other methods have also appeared such as life cycle assessment that is a standardized methodology provided by the International Standardization Organization (ISO 14040–14043). The latter evaluates the environmental impacts of a product (good or service) during its entire life cycle based on mass and energy conservation, based on the first law of thermodynamics (Balocco et al. 2004). Then, the second law of thermodynamics induced the notion of exergy that led to exergy analysis (EA) (Sciubba and Ulgiati 2005; Beccali et al. 2003). Consequently, exergetic life cycle analysis (ELCA) emerged as an enhancement of the methodologies associated with the first and second laws of thermodynamics. It has been demonstrated as a method for quantifying the depletion of natural resources in the LCA and as a valuable tool for assessing the efficiency of natural resources usage (Cornelissen and Hirs 2002).

The quantity and the scale of the environmental burdens caused by energy exploitation and generation are strongly connected to the efficiency of the applied technologies (Dicorato et al. 2008). Consequently, increased efficiency of energy processes involved in the life cycle of a product leads to reduced use of natural recourses, environmental impacts, and energy losses (Pepermans et al. 2005; Dincer and Rosen 1999). Furthermore, the renewable energy sources and technologies, such as photovoltaics and wind turbines, suggest a vital component to the sustainable development approach (Dovì et al. 2009). Although, use of renewable energy sources and technologies cannot guarantee zero environmental impacts, they can provide an environmentally sound alternative in the satisfaction of energy demand, compared to the conventional resources and technologies (Panwar et al. 2011; Sims et al. 2003; Boudghene Stambouli and Traversa 2002).

In this context, this paper implements the ELCA methodology to a large-scale, grid-connected, photovoltaic (PV) system with energy storage that is assumed to fully serve the needs of an island in electric power.

## 2 Life cycle assessment

Life cycle approach suggests one of the basic ideas for the implementation of sustainable development (Hertwich 2005; Klöpffer 2003). The required support for the application and implementation of the life cycle approach, in the framework of sustainability, is provided by a group of operational methods, called Environmental Systems Analysis Tools (ESAT) (Höjer et al. 2008; Finnveden and Moberg 2005). ESAT framework suggests structured methods of analysis, assessment and communication (Kiker et al. 2005; Wrisberg et al. 2002). The application of ESAT provides information, which can be used in communication and education level, but more importantly, it provides the necessary framework for the environmental decision making process (Ness et al. 2007).

Life cycle assessment (LCA) is one of the most important and comprehensive ESAT for the evaluation of the environmental profile and performance of a process's, product's, or

service's life cycle (Koroneos et al. 2005a, b; Rebitzer et al. 2004). LCA suggests an integrated and comprehensive "cradle-to-grave" approach, which examines the life cycle, from the acquisition of raw materials and energy production to the use and the final disposal phase of a product or process (Giljum et al. 2011; Guinée 2002; Arena et al. 2003). It provides the required support to the environmental decision making process, by making comparisons between the environmental impacts categories of the available alternatives on process, product, or service level (Samaras and Meisterling 2008; Weisser 2007).

The International Standardization Organization developed a series of standards to describe a consistent and robust methodology for LCA implementation, as part of the ISO 14000 series on environmental management (Georgakellos 2012). LCA studies have four main elements, which are described in ISO 14040 (ISO 2006) as follows:

1. Goal and scope definition, which serves to define the extent and purpose of the study and describe the product or process examined. Moreover, the context of the study, system boundaries, and environmental effects to be reviewed are established.
2. Inventory analysis or LCI, which consists in the collection and analysis of the energy inputs-outputs, material consumption, and environmental burdens (i.e., air emissions, solid waste, water discharges, etc.), are identified and quantified.
3. Impact Assessment, which supports evaluation of the magnitude and significance of potential impacts of a system on human and ecosystem. From a practical viewpoint, impact assessment organizes LCI inputs and outputs into specific impact categories and creates an indicator based on the results of these impacts.
4. Interpretation, which is the final stage of evaluating inventory analysis and impact assessment which draws conclusions and provides recommendations for environmental improvements (International Organization for Standardization 2006; Ardente et al 2005; Beccali et al. 2003). It takes into consideration the uncertainties and the assumptions made during the previous stages of the study.

## 3 Exergy analysis

Exergy is defined as the maximum attainable work which can be produced by a system, matter, or energy flow, as it comes in thermodynamic equilibrium with the reference environment, through sequential reversible processes (Koroneos et al. 2003; Szargut et al. 1998). Exergy reflects a system's or flow's measure of potential to cause a change as a consequence of not being completely in stable equilibrium with the reference environment (Rosen et al. 2008; Dincer and Cengel 2001). The methodology of exergy analysis (EA) is based on the principle of energy preservation (first thermodynamic law) and in conjunction with the principle of entropy destruction (second thermodynamic law) attempts to analyze, design, and optimize energy systems (Granovskii et al. 2008; Rosen and Dincer 2001). EA reveals the parts of a system where the available work, embodied in natural resources, is not efficiently utilized or, in other words, where efficiency gains can be found (Rosen et al. 2008; Cornelissen 1997). According to the second thermodynamic law, in all irreversible processes, the entropy of the adiabatic system is increased. The irreversibility (I) of a process is related to the produced entropy (Δs) by the following equation (Pauluis and Held 2002):

$$I = T_0 \times \sum \Delta s \tag{1}$$

where $T_0$ is the temperature of the reference environment. Consequently, the EA results are determined by the assigned reference environment.

The irreversibility or exergy losses can be also calculated from the exergy balance by subtracting the outcoming from the incoming exergy flows (Lior and Zhang 2007; Cornelissen 1997):

$$I = \sum \Delta E_x = \sum_{\text{in}} E_{\text{x}\ i} - \sum_{\text{out}} E_{\text{x}\ j} \tag{2}$$

where $E_{\text{X}\ i}$ is the exergy content of the incoming flow $i$, and $E_{\text{X}\ j}$ is the exergy content of the outcoming flow j.

Consequently, the exergetic efficiency ($n_{\text{exergetic}}$) of a system can be calculated based on the exergy flows in the exergy balance (Hammond and Stapleton 2001; Gong and Wall 1997):

$$\eta_{\text{exergetic}} = \frac{E_{\text{X out}} - E_{\text{X waste}}}{E_{\text{X in}}} = \frac{E_{\text{X pr}}}{E_{\text{X in}}} \tag{3}$$

where $E_{\text{X in}}$ is the total incoming exergy flow of the system, $E_{\text{X out}}$ is the outcoming exergy flow, $E_{\text{X waste}}$ is the exergy flow wasted in the environment, and $E_{\text{X pr}}$ the exergy flow that is produced by the system.

EA results can be presented in exergy flow diagrams or, so called, Sankey diagrams (Mateos-Espejel et al. 2011; Koroneos et al. 2005a, b). An exergy flow diagram forms a useful tool that illustrates inflows, outflows, and the amount of exergy consumed within boundaries of the system or process under consideration (Hepbasli 2008).

## 4 Exergetic life cycle assessment

EA within methodological framework of LCA can indicate the depletion of natural resources or define exergy losses in the

stage of improvement assessment (Jeswani et al. 2010; Finnveden and Ostlund 1997). In the characterization phase of impact assessment (LCA), scientifically established characterization factors can be used to convert and combine inventory analysis results into representative impact indicators in fields of human health, health of the ecosystem, and natural resources (Hutchins and Sutherland 2008). The contribution ($C$) of an inflow or an outflow can be calculated (Finnveden and Ostlund 1997) as follows:

$$C_{ij} = Q_{ij} \times M_i \tag{4}$$

where $Q_{ij}$ is the characterization weighting factor of the flow $i$ for the impact category (or subcategory) $j$, and $M_i$ is the incoming or outcoming flow $i$ for the impact category (subcategory) $j$.

Exergy consumption can be used as a characterization factor for abiotic reserves and flows of natural resources, but it can also be used to describe the competition of biotic resources. In LCA, the inflows should be the natural resources as they are originally acquired from the environment. Specification of weighting factor characterization defines the exergetic contribution (exergy content) of inflows and outflows, in terms of chemical exergy for each substance (either raw material or emission) (Bastianoni et al. 2005; Finnveden and Ostlund 1997):

$$E_{\mathrm{x\ ch},n} = \Delta G_f + \sum_i \mathrm{x}_i \times e_{\mathrm{x\ ch,n,i}} \tag{5}$$

where $E_{\mathrm{X\ ch},\ n}$ is a chemical exergy of chemical compound n in [$\mathrm{KJ_{ex}}$/mol], $\Delta G_f$ is the Gibbs free energy of formation of chemical compound $n$, expressed in [$\mathrm{KJ_{ex}}$/mol], $x_i$ is the mole fraction of the $i$ substance of compound $n$ in kilomole (kmol), and $e_{\mathrm{X\ ch},n,i}$ is the chemical exergy in reference state of $i$ substance of compound $n$.

Existing available data in literature on the exergy content of abiotic deposits, both for exergy content of ores and fossil fuels deposits, are particularly helpful for characterizing weighting factors $Q_{ij}$, (Liao et al. 2012). EA can be applied to the inventory analysis stage of LCA or to the characterization phase of the Life Cycle Impact Assessment (Mirandola et al. 2010). In the first case, exergy can be used in characterization by summing up the inflow's exergy content without assigning weighting factors (Finnvenden and Ostlund 1997). In the previously mentioned case, it must be clearly stated that exergy consumption is not able to describe the impacts of the depletion of natural resources to their full extent (Steen 2006). In the latter case, the characterization weighting factors are used to express the exergy content per incoming quantity (Sciubba 2012).

The methodological framework of ELCA is similar to that of LCA (Talens Peiró et al. 2010). Definitions of goal and scope in both ELCA and LCA tools are identical, but the inventory analysis of ELCA is much more comprehensive and appropriate, even at an early design stage (Medyna et al. 2009). An ELCA study in an advanced development stage still requires a detailed inventory of the mass and energy flows within boundaries set for the system examined (Lombardi 2003).

ELCA examines the impacts that arise from the consumption of natural resources under the scope of exergy, in the methodological framework of LCA (Cornelissen and Hirs 2002). Moreover, EA detects where the exergy losses take place and by the improvement assessment allows the evaluation of the alternatives in order to minimize the irreversibility of the examined product's or processes' life cycle (Belhani et al. 2008). Thus, ELCA serves as a measure of energy and material resource depletion as well as a measure of the technical efficiency of systems under study (Costa et al. 2001). Additionally, all exergy inflows, outflows, losses, and process irreversibilities are determined, taking also into account disaggregated exergy values associated with environmental releases (Beccali et al. 2003). According to a simplified approach, the distinct life cycle stages can be overlooked, and life cycle can be considered as a single process (black-box process), with inflows and outflows (Toxopeus et al. 2006). Consequently, an exergy indicator arises that illustrates the life cycle irreversibility and can be calculated by subtracting the exergy that remains available after completion of life cycle from the total incoming exergy flow of the system (Toxopeus et al. 2006):

$$E_{\mathrm{x\ ind.}} = \sum_{\mathrm{in}} E_{\mathrm{x\ fuel}} + \sum_{\mathrm{in}} E_{\mathrm{x\ raw}} - \sum_{\mathrm{out}} E_{\mathrm{x\ waste}} - \sum_{\mathrm{out}} E_{\mathrm{x\ f.u.}} \tag{6}$$

where $E_{\mathrm{X\ fuel}}$ is the incoming exergy content of fuel, $E_{\mathrm{X\ raw}}$ is the incoming exergy content of raw material, $E_{\mathrm{X\ waste}}$ is the exergy content of waste, and $E_{\mathrm{X\ f.u.}}$ is the exergy content of the functional unit that is produced during the life cycle. The numerical value of each exergetic flow is suggested to be simply associated with an equal characterization weighting factor. Concerning application of the exergy indicator of irreversibility, there is no distinction between renewable and non-renewable exergy sources. On the contrary, this indicator provides an evaluation of the amount of exergy required in supporting product life cycle (Sciubba and Ulgiati 2005).

The notion of exergy is strongly related to the approach of sustainable development, and methodologies that examine the life cycle of a given product or process under the scope of exergy can be applied in the framework of the sustainable development (Rosen et al. 2008). According to the "black-box" process approach and assuming the life cycle of a system as an energy process, a dimensionless indicator can be assigned that illustrates sustainability of the whole process.

This indicator is called exergetic eco-efficiency ($n_{eco}$) and is given by the following equation (Toxopeus et al. 2006):

$$\eta_{\text{eco}} = \frac{\eta_{\text{exergetic}} \times (F_{n-r} + F_r)}{F_{n-r} + \eta_{\text{exergetic}} \times F_{\text{r}}} \tag{7}$$

where $F_{n\text{-}r}$ is the non-renewable exergy feed, $F_r$ is the renewable exergy feed, and $n_{\text{exergetic}}$ is the exergetic efficiency of the life cycle at an aggregate level taking into account all flows and processes at once.

According to Eq. 7, exergetic eco-efficiency takes into account the efficiency of consumption for both renewable and non-renewable sources throughout the entire life cycle of the product or process under study (Dewulf et al. 2005). Consequently, a higher value of the indicator represents a more sustainable alternative (Toxopeus et al. 2006; Dincer and Rosen 2004).

## 5 Application of a large-scale, grid-connected, polycrystalline PV system in the Greek Island of Nisyros

### 5.1 Life cycle assessment of the PV system

Large-scale grid-connected PV systems constitute an important application of the PV technology due to the fact that they operate as the main source of electricity supply for the national grid. The basic component of a PV system is an array of solar panels (Yang et al. 2007). In our case scenario of the Nisyros Island, excessively generated electric power of PV system is assumed to be stored in batteries for supporting energy demands during the night. At the same time, integrity of the local power system is secured with the diesel power unit of the Dodecanese interconnected power system, which is set at standby to support conditions of extreme demand or when the solar radiation intensity is minimized (Fig. 1) (Koroneos et al. 2006a; Duić and da Graça Carvalho 2004). Moreover, a PV system includes devices for voltage conversion and configuration of the electric power produced (Blaabjerg et al. 2004). The PV system, assumed for the application scenarios in Nisyros, includes DC/AC inverters, batteries, and steel foundations of the ground mounting, besides PV modules (Koroneos et al. 2006b). Mounting of the PV system on the ground should be given careful consideration in order to withstand forces in all directions due to high winds.

The implementation of LCA framework has been realized according to ISO 14040 (International Organization for Standardization 2006) and complying with the International Life Cycle Data System (European Commission–Joint Research Centre–IES 2010). Four discerned cases were studied, which reflect current and future evolution of solar cells' manufacturing technology (Stylos and Koroneos 2014): base case, improved case, forward case, and KC-65T case, with the latter being an application of the base case using a specific type of solar panel widely available in the market by Kyocera Corporation (2013). The base case is chosen in such a way that it represents a good estimate of the present state of production technology and environmental control measures (Stoppato 2008). The improved case is defined as the technology, which has been already reached and will be commercially available widely within next couple of years. The forward case represents an optimistic view on production technology available within the next 5 years (Swanson 2006). Finally, KC-65T case is an application of a PV module, which is already in the market. Thus, comparisons can be made among case scenarios, and some useful conclusions can be drawn. In addition, base case assumes use of PV panels with a solar cell efficiency of 14 % and a total lifetime of 30 years. Important aspects of the improved case scenario are the increase of solar cell efficiency at 17 % and a module life time of 40 years. As far as the forward case is concerned, solar cell technology is expected to reach an encapsulated cell efficiency of 20 %, readily marketable, and supporting power generation for half a century since assembly (Stylos and Koroneos 2014). The KC-65T case is based on the technical specifications of KC-65T PV module, similar to those of base case scenario, with slightly larger dimensions and solar cell efficiency (14.1 %) (Kyocera Corporation 2013). Regarding specifications of DC/AC inverters, batteries, and steel foundations of panels, there is not any kind of discrimination among various PV cases. Nevertheless, it is important to mention that for the electrolytic chrome coated steel (ECCS) foundations, three cases have been considered: base case, improved, and forward case. It is the difference in lifetime span of PV cases that affects replacements of batteries, hence total number of battery items as well as the variations in dimensionality of PV modules that

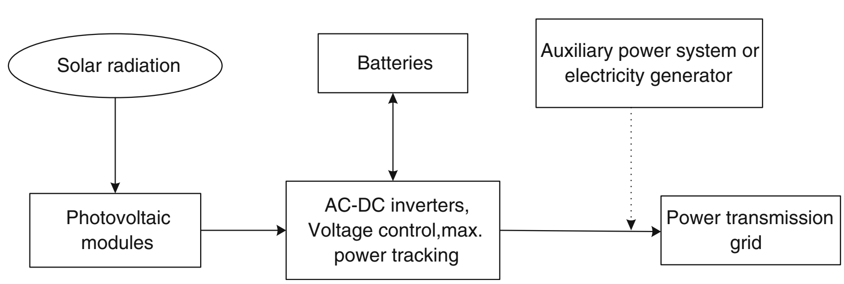


Fig. 1 Schematic diagram of a large-scale, grid-connected PV system with energy storage (Koroneos et al. 2006a)

determines design of PV arrays, namely total mass of ECCS steel. In KC-65T case, calculations for the batteries and steel foundations are identical with those of base case scenario (Stylos and Koroneos 2014).

### *5.1.1 Description and analysis of PV module*

Photovoltaic modules consist of a number of solar cells relevant to the module area. The most important part of a solar cell is the semiconducting layers, where the electron current is created. There are a number of different materials suitable for manufacturing these semiconducting layers, and each has benefits and drawbacks (Goetzberger et al. 2003). There is no ideal material for all types of cells and applications, but the most important still remains silicon with its various structural forms (Goetzberger et al. 2002). The subsystem of PV modules includes the basic raw materials (silica, aluminum, glass, EVA, and Tedlar), relevant processes, and energy sources for PV-module manufacturing (Fig. 2) (Koroneos et al. 2006a). Moreover, inventory analysis of PV-module subsystem includes the transportation of raw materials and energy sources to the manufacturing facilities in Japan (Stylos and Koroneos 2014).

As shown in Fig. 2, aluminum is one of the basic raw materials used for PV-module framing (Fthenakis and Kim 2011; Richards and Watt 2007). The waste produced by aluminum manufacturing processes is considered to be fully recycled (Kikuchi 2001). Two subcases have been considered regarding aluminum recycling for the final disposal phase of PV module life cycle. According to the first subcase, denoted as Al 0 %, aluminum embodied has not been recycled, while in the second one (Al 50 %), the aluminum consumed for building the module frames contain 50 % secondary (recycled) aluminum (Koroneos et al. 2006a).

Tedlar and EVA are two well-known plastics in PV industry being used in solar cell encapsulation process (Fig. 2). Tedlar plastic serves as the backsheet of PV module supporting the entire structure of it. An EVA (ethylene vinyl acetate) polymer foil is used for welding solar cells with the glass sheet and the Tedlar backsheet (Nowlan et al. 2005). The glass manufacturing and assembly processes are also included in the PV module's subsystem (Fig. 2).

In the operation stage of PV modules' life cycle, demands in energy, and materials from primary resources, other than consuming small amounts of self-generating electricity for system controls, have been considered to be negligible (Koroneos et al. 2006b). Moreover, during the operation of PV system, zero emissions and waste are released by the PV modules (Battisti and Corrado 2005; Fthenakis 2003). Concerning final disposal of PV modules, no recycling processes are applied. Thus, after disassembly of the aluminum frame, PV modules are disposed as solid waste (Ito et al. 2011).

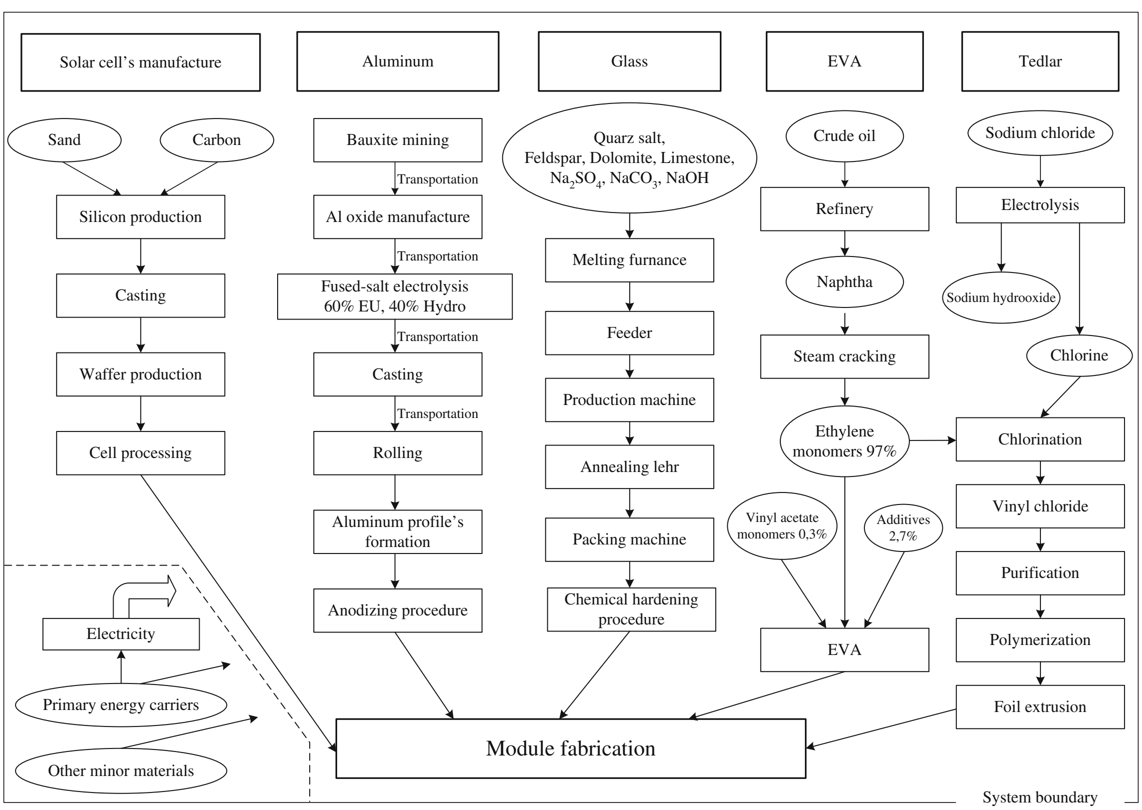


**Fig. 2** PV module fabrication flow diagram (Nowlan et al., 2005; Koroneos et al. 2006a)

#### *5.1.2 Analysis of PV system balance-of-system components (BOS components)*

Except for PV-modules, all the complementary equipment that contributes to the operation of PV system forms the balance-of-system component arrangement (BOS-Components). These components include DC/AC inverters, batteries, steel mounting frames, and power conditioning electronics (Hammond et al. 2012).

DC/AC inverters convert dc power produced from PV modules into ac power in order to supply the grid (Eltawil and Zhao 2010). The PV system presumed in this study includes two 500 kVA DC/AC inverters (SMA Solar Technology AG 2013; Aixcon Powersystems 2013). In the PV system's life cycle, only one set of DC/AC inverters is required. On the contrary, batteries' installation is replaced every 10 years, exerting a major effect on the good standing of the whole system that could change dramatically exergy evaluations (Rydh and Sandén 2005). The batteries required for current PV system are manufactured by Hoppecke AG (OPzS series) and have a 1,200-Ah capacity (Hoppecke Batterien 2014).

The energy demands and emissions released for manufacturing processes and transportation for BOS components have all been taken into account. Concerning the transportation of PV system components, PV-modules have been exported from Japan to Greece traveling 9,400 km by cargo ship; inverters, batteries, and steel foundations are imported from Germany to Greece, assuming road transport covering a 1,650-km distance by a 40-tonne truck. All PV-system components have been transhipped to a freighter traveling 470 km from the port of Piraeus to the island of Nisyros where the assembly procedures of PV systems have taken place (Stylos and Koroneos 2014). The resource used for transportation is fuel oil (diesel) representing 7.6 % of total energy inflows and the air emissions due to transportation amount at 6.5 % of total emissions, respectively.

#### *5.1.3 Design, application, and results of PV system life cycle assessment*

Design and application of the aforementioned PV system is based on the monthly electricity consumption data and variation of the solar irradiation, per surface unit, on Nisyros Island (for the different pitch angles of PV-modules) (Koroneos et al. 2006b). Additionally, correction factors are taken into account in order to calculate the losses by the transformation of the solar radiation into electricity on the PV modules, the transfer of the electric power, or by the transformation of the dc voltage into ac power. Thus, based on the electricity demand on Nisyros Island and the various PV case scenarios, the number of required PV modules of the installation is calculated. Due to the fact that the PV system is designed to operate on a yearly basis, PV system characteristics are adapted to the month with the lowest average solar irradiation (February for Greece) in order to be on the safe side (Zhou et al. 2010). Estimated electricity storage needs depend on the local weather conditions (maximum number of consecutive clouded days), the electricity consumption peaks in Nisyros Island, and the desired reliability of the PV system. Minimum autonomy of PV system is set at 3 days in the autumn-winter period and 6 days in the spring-summer period, based on historical data for power consumption (Koroneos et al. 2006b). Final results and basic characteristics of the assumed PV system serving Nisyros Island are summarized on Table 1.

### 5.2 Exergetic life cycle assessment of the PV system in Nisyros

As it was previously stated, the ELCA methodology is similar to that of LCA (Talens Peiró et al. 2010). In the current ELCA study, a straightforward approach of life cycle as black-box process (input/output analysis) is being adopted, meaning that energy consumption and emissions are allocated according to the electricity produced by the system (Grubb and Bakshi 2011; Khasreen et al. 2009); More specifically, PV system's life cycle is considered as a single energy process, without examining the processes that are involved in each stage of the cycle, indicating the total exergetic "expense" (Corrado et al. 2006); the advantageous nature of the black-box approach in comparison to process analysis is due to the fact that input/output analysis is considered to be more comprehensive and at the same time process analysis can be significantly incomplete due to complexities that arise from goods and services (Lave et al. 1995). Thus, based on inventory analysis results of the corresponding LCI databases (Ecoinvent 2011), the exergy balance and ELCA indicators are estimated.

#### *5.2.1 System boundaries, functional unit, and reference environment of the PV system*

The goal of ELCA study suggests an extension of the scope of a similar LCA study focusing on the exergetic parameters that are related to the life cycle of the PV installation (Himpe et al. 2013). The systems boundaries are identical with those determined in the LCA study. More specifically, the system encloses the acquisition of raw materials, transportation to the manufacturing site in order to fabricate PV-modules, manufacture, and assembly of the PV modules. The system also includes the batteries, DC/AC inverters, and steel foundations (BOS components). The stage of use of the system represents the operation phase of the PV system, which differs for each of the four PV technology cases. As far as the life cycle stage of final disposal is concerned, the parts of PV installation are supposed to be disposed as solid wastes.

**Table 1** Characteristics of installed PV large-scale system in the Nisyros Island according to various PV cases (Stylos and Koroneos 2014)

| | Unit | Base case | | Improved case | | Forward case | | KC-65T case | |
|---|---|---|---|---|---|---|---|---|---|
| | | Al 0 % | Al 50 % | Al 0 % | Al 50 % | Al 0 % | Al 50 % | Al 0 % | Al 50 % |
| Total installed power, $P_{inst}$ | [kW] | 293.28 | 293.28 | 296.21 | 296.21 | 296.43 | 296.43 | 294.12 | 294.12 |
| Number of PV-modules, $N_{mod}$ | – | 5,140 | 5,140 | 2,640 | 2,640 | 1,640 | 1,640 | 4,902 | 4,902 |
| Total PV-module area, $A_{mod}$ | [m$^2$] | 2,246 | 2,246 | 1,711 | 1,711 | 1,640 | 1,640 | 2,397 | 2,397 |
| PV-module surface | [m$^2$] | 0.44 | 0.44 | 0.648 | 0.648 | 1 | 1 | 0.489 | 0.489 |
| Coverage factor, $s_{co}$ | – | 0.82 | 0.82 | 0.86 | 0.86 | 0.9 | 0.9 | 0.75 | 0.75 |
| Temperature correction factor, $S_T$ | – | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 | 0.91 |
| Needs in ECCS steel | [kg] | 56,229 | 56,229 | 36,159 | 36,159 | 30,144 | 30,144 | 65,621 | 65,621 |
| Number of batteries, $N_b$ | – | 520 | 520 | 520 | 520 | 520 | 520 | 520 | 520 |
| Number of batteries replacement during the life cycle, $N_r$ | – | 2 | 2 | 3 | 3 | 4 | 4 | 2 | 2 |
| Number of DC/AC inverters of the entire life cycle, $N_I$ | – | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Peripherals system ratio, $\alpha_{BOS}$ | – | 0.735 | 0.735 | 0.735 | 0.735 | 0.735 | 0.735 | 0.735 | 0.735 |
| PV module system operation ratio, $\lambda_{mod}$ | – | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| Electricity consumption on the Nisyros Island, $E_{Nis.an}$ | [KWh/year] | 246,050 | 246,050 | 246,050 | 246,050 | 246,050 | 246,050 | 246,050 | 246,050 |
| Life time, Lt | [yr] | 30 | 30 | 40 | 40 | 50 | 50 | 30 | 30 |
| Annual electricity production, $E_{el\ LC.}$ | [GJ] | 1,143 | 1,143 | 1,155 | 1,155 | 1,156 | 1,156 | 1,147 | 1,147 |

The functional unit used in the ELCA study is 1 $MWh_{ex}$, and all the values are expressed in terms of $MWh_{ex}$. In order to make comparisons between the different PV technology cases or among the examined electricity production technologies, the exergetic values are reduced to the produced exergy unit [$MWh_{ex\ prod}$].

Another important parameter of ELCA that must be determined is the reference environment. The reference environment, according to bibliography, simulates on a thermodynamically "dead" planet, where all the substances have reacted, interfered, and are fully dispersed (Szargut et al. 2005).

### 5.2.2 *Inflows exergy content of the PV system*

The inflows of PV system's life cycle, as they were formed in the inventory analysis of the LCA study (Stylos and Koroneos 2014), provide the necessary base on which the total incoming exergy to the PV system is formed. The incoming flows to the PV system's life cycle include the materials, the energy sources, the solar radiation, and the reusable waste for each of the examined PV cases.

The term "materials," mentioned above, incorporates the feedstock, in the form that is found in the natural environment, used for the acquisition, manufacturing, operation, and final disposal of the PV system components. The exergy content is calculated in terms of chemical exergy of the materials involved, based on Eq. 8. All required data for the calculation of the materials chemical exergy is taken from various references (Yilanci et al. 2011; Dewulf et al. 2007; Finnvenden and Ostlund 1997) as well as for the ore deposits is concerned (Dewulf and Van Langenhove 2002).

Another category of incoming flows is the one related with sources that supply with energy the entire life cycle of the PV system. In this category of inflow, the solar radiation is excluded. More specifically, the fossil fuels' exergy content can be calculated based on the heating value (HV) according to the following equation (Yildiz and Güngör 2009; Finnvenden and Ostlund 1997):

$$E_{x\ ch} = \varphi \times \mathrm{HV} \tag{8}$$

where $E_{X\ ch}$ is the chemical exergy of the examined fuel, $\varphi$ represents the chemical exergy to heating value ratio, which varies according to the molecular composition of each fuel, and HV stands for the heating value of the fuel. Values of the $\varphi$ ratio and the average lower heating value (LHV) of the fuels used in calculations have also been acquired from recent bibliography (U.S. Department of Energy 2008; Ayres and Warr 2005; Ayres et al. 2006).

Solar radiation provides the most significant energy source of the PV system's life cycle. Additionally, due to the separate calculation method of the solar radiation's exergy content, it allows to be considered as a distinguished exergetic inflow to the PV systems life cycle (Dewulf et al. 2008; Szargut 2005). At this point, it must be clearly stated that solar radiation exergy content is not calculated based on the total solar radiation that prostrates on the PV modules. On the contrary, the calculations refer to the amount of solar radiation exergy

that the PV modules can utilize. The efficiency of the PV modules depends on the relative temperature difference between the PV modules and the natural environment and on the PV modules' surface pollution (dirt, leafs, insects etc.). The temperature correction factor ($s_{\mathrm{T}}$) is a dimensionless coefficient that adjusts the efficiency of the solar cells ($\eta_{\pi}$) to the relative temperature of the environment and is given by Eq. 9 (Luque and Hegedus 2011):

$$s_{\mathrm{T}} = \frac{I_{\mathrm{T_{PV}}}}{I_{\mathrm{T_e}}}, \tag{9}$$

where $I_{\mathrm{Tpv}}$ is the mean daily solar irradiation at the temperature of PV-module, and $I_{\mathrm{Te}}$ is the mean daily solar irradiation at the environmental temperature, per square meter of module area. This correction factor multiplied by the peripherals system ratio contributes in calculating the overall PV module system operation ratio. Peripherals system ratio is the product of batteries' ratio, inverters' ratio, and wiring ratio and is actually representing the efficiency of system components other than PV modules.

The clearness factor ($s_{\mathrm{C}}$) reflects the PV module's surface pollution and is given by the ratio of the electric power produced by the polluted PV module to the electric power output of a clear PV module. In the present study, the clearness factor is considered to be equal to 0.9 (Koroneos et al. 2006a). The solar radiation exergy content is also related to the coverage factor ($s_{\mathrm{CO}}$) of the PV modules. The coverage factor of the PV modules derives from the ratio of the effective solar cells' surface to the total surface of the PV module and differs for each of the examined PV cases (see Table 1). Thus, based on the PV modules' pitch angle, the solar irradiation data for Nisyros Island, the average daily air temperature, temperature correction factor, the clearness factor, and the exergy factor of solar radiation ($\mathrm{e_f}$), which is according to bibliography equals to 0.93 (Joshi et al. 2009), emerges the exergetic content of solar radiation. The incoming exergy of the solar radiation to the PV system is given by the equation as follows:

$$E_{\mathrm{x\ sol,LC}} = \left[ \sum_{i=1}^{12} \Pi_{\mathrm{irr,.mo}\ \ i} \times s_{\mathrm{T}\ \ i} \right] \times s_C \times s_{\mathrm{co}} \times e_f \times Lt \tag{10}$$

where $E_{\mathrm{X\ sol,LC}}$ is the incoming exergy of the solar radiation for the PV system's life cycle, $\Pi_{\mathrm{irr,mo}\ i}$ represents the average intensity of the solar radiation in Nisyros Island for the month $i$, $s_{\mathrm{T}}$ is the temperature correction factor for the average air temperature of month $i$, $s_{\mathrm{C}}$ is the clearness factor, $e_{\mathrm{f}}$ is the exergy factor of solar radiation, and Lt is the expected life time of the PV system measured in years (Hacatoglou et al. 2011; Badescu et al. 1996).

The final exergetic inflow to the PV system's life cycle includes the reusable wastes. Obviously, the reusable wastes exergy content is assigned with a negative value in the life cycle exergy balance, as it is suggested for the utilizable part of the PV system's life cycle waste (Cherubini et al. 2008).

### *5.2.3 Calculation of the outflows exergy content and electricity generated by PV system*

Based on the inventory data analysis stage of the LCA study, the exergetic outflows of the PV system's life cycle can be determined. The outcoming flows of the PV system's life cycle include the air emissions, water and underground pollutants, solid waste, transferred substances, the rest of the waste, and the electricity generated for each of the PV cases examined (Hepbasli 2008).

The first category of chemical substances that contribute to the formation of the exergy outflows is the atmospheric emissions released from the life cycle of the PV system. Chemical exergy of the released air emissions, for the conditions of reference environment, is either obtained directly from related bibliography or calculated according to the Eq. 10 (Morris and Szargut 1986). Additionally, due to the variety of compounds that are included in some categories of air emissions (aromatic hydrocarbons, polycyclic aromatic hydrocarbons, non-methanic volatile organic compounds etc.), the exergetic content is calculated based on specific and representative chemical compounds of each category, in equal portion. The ash and the particles released during PV system's life cycle are considered to have negligible exergetic content.

The water pollutants, underground emissions, and waterborne substances consist another category of substances that contribute to the formation of the exergy outflows of the PV system's life cycle. The exergetic content of inorganic compounds and ions dissolved in aquatic solution, for the conditions of reference environment, is obtained from bibliographic data (Ludovisi et al. 2012). Concerning the organic compounds dissolved in waste water, the chemical exergy is expressed with equation (Tai et al. 1986):

$$E_{\mathrm{x\ ch,org},i} = 13,6 \times \mathrm{T}OD_i \tag{11}$$

where $E_{\mathrm{X\ ch,org,\ i}}$ is the chemical exergy of the organic compound $i$ in [J/l], and $\mathrm{TOD}_i$ represents the total oxygen demand of the organic compound $i$ in [mg/l]. The data on the total oxygen demand (TOD) of the organic compounds is found in bibliography (Tai et al. 1986). Moreover, the chemical exergy of the total organic carbon (TOC) in waste water is approached by Eq. 12 (Tai et al. 1986):

$$E_{\mathrm{x\ ch,org},i} = 45 \times \mathrm{T}OC \tag{12}$$

where $E_{\mathrm{Xch,org,}\ i}$ is the chemical exergy of the total organic carbon in waste water [J/l], and TOC is the total organic carbon dissolved in waste water [mg/l].

Moreover, exergy outflows of the PV system's life cycle include solid waste or/and other waste (Morris and Szargut 1986).

The beneficial part of the exergy outflow suggests the produced functional unit of the PV system's life cycle, i.e., electricity generated by the PV system. The exergy factor of the electricity is equal to one (Wall 2001) and, consequently, the exergy content of the power generated for the entire life cycle of the PV system is equal to its energy content.

### *5.2.4 Life cycle irreversibility of the PV system*

The life cycle of the PV system can be approached as a real energy process that converts the incoming exergy (materials, energy sources, solar radiation, and reusable wastes) into useful exergy outflow (electric power), non-usable outflow (wastes, emissions), and exergy losses. Consequently, the irreversibility or exergy losses that are introduced throughout life Cycle of PV system can be calculated from the life cycle exergy balance by subtracting the total outcoming from the total incoming exergy flows, as indicated in Eq. 13 (Cornelissen 1997):

$$I = \sum_{\text{in}} E_{\text{x}\ i} - \sum_{\text{out}} E_{\text{x}\ j} = \sum_{in} E_{\text{x es}} + \sum_{in} E_{\text{x}\ m} + \sum_{in} E_{\text{x sol}} - \sum_{\text{out}} E_{\text{x e-w}} - \sum_{\text{out}} E_{\text{x f.u.}} \quad (13)$$

where $E_{\text{X es}}$ stands for the incoming exergy content of the PV system's life cycle energy sources, $E_{\text{X}\ m}$ represents the incoming exergy content of the PV system's life cycle materials, $E_{\text{X sol}}$ is the incoming exergy content of the solar radiation during PV system life cycle, $E_{\text{X}\ e\text{-}w}$ is the outcoming exergy content of the emissions and wastes during PV-system life cycle, and $E_{\text{X f.u.}}$ represents the useful exergy content of the produced functional unit (electricity) within PV system's life cycle.

In the calculation of the PV system life cycle's irreversibility, a characterization weighting factor, equal to one, is assigned to the numerical value of each exergy flow (González et al. 2003; Toxopeus et al. 2006).

### *5.2.5 Life cycle exergy balance and exergetic eco-efficiency of the PV system*

The formation of the exergy balance allows evaluation of the incoming exergy efficiency, in respect to the life cycle of the assumed large-scale PV system (all PV cases apply). The exergetic efficiency ($n_{\text{exergetic}}$) for the entire life cycle of the PV system, according to Eq. 3, is calculated at an aggregate level for all flows involved by the ratio of the electricity generated to the total incoming exergy during the life time of the PV system.

The incoming exergy of the PV system can be alternatively expressed in terms of renewable and non-renewable incoming exergy (Toxopeus et al. 2006). Renewable exergy feed ($F_{\text{r}}$) includes the exergy content of renewable energy sources (solar radiation, wood, and waterfall energy) that contribute to the formation of the total incoming exergy of PV system's life cycle. On the contrary, non-renewable exergy feed ($F_{n\text{-}r}$) includes the exergy content of non-renewable energy sources (oil, petrol, lignite, coal, etc.) during the PV system's life cycle. Consequently, exergetic eco-efficiency ($n_{\text{eco}}$) for the assumed PV system application in the Nisyros Island can be estimated, for all PV case scenarios under examination.

### *5.2.6 Final results and exergy flow-Sankey diagrams of the PV systems' ELCA*

Based on the results of the LCI's and the extensive calculations, the ELCA final estimations of the PV system in Nisyros are deduced, and for all PV cases and subcases related to aluminum recycling. ELCA results are presented in Table 2.

ELCA results show that the differences in energy/exergy flows between 50 % aluminum recycling and no-recycling subcases are minor in all PV case scenarios, but they need to be further analyzed. In more specific, recycling of 50 % (Al 50 %) of the used aluminum in frames leads to a slight decrease of the materials exergy content. The decrease of the materials exergy content can be explained by the fact that the aluminum recycling process reduces the energy demand and use of materials of the PV system's life cycle. Thus, the effect of aluminum recycling in each of the PV cases is more clearly illustrated by the increase of the reusable waste exergetic contribution. The reduced use of raw materials and energy sources, that the aluminum recycling processes involve, lead to reduced environmental burdens. Consequently, the reuse of the consumed aluminum (Al 50 %), for all examined PV cases, leads to both reduced life cycle Irreversibility (exergy losses) and reduced exergy content of some categories of outflows (air emissions, water emissions, and other waste). Additionally, if the life cycle incoming exergy is expressed in terms of non-renewable and renewable exergy feed, the reuse of the consumed aluminum (Al 50 %), for all the examined PV cases leads to decreased non-renewable exergy contribution. Additionally, in all PV cases, aluminum recycling (Al 50 %) decreases slightly the renewable exergy contribution, due to less energy consumed during the whole recycling chain (Hoque et al. 2012). Moving gradually from the base case and its application (KC-65T case) to the forward case, the sustainable prospective of the PV systems is demonstrated. The increased exergetic

**Table 2** Final ELCA results of various PV case scenarios concerning the Nisyros Island

| | | Unit | Base case | | Improved case | | Forward case | | KC-65T case | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Al 0 % | Al 50 % | Al 0 % | Al 50 % | Al 0 % | Al 50 % | Al 0 % | Al 50 % |
| Life cycle exergy inflow | Materials, $E_{xtot\ m}$ | [$MWh_{ex}$] | 1784.96 | 1781.5 | 2152.5 | 2149.66 | 2601.43 | 2599.92 | 1754.212 | 1746.28 |
| | Energy sources, $E_{xtot\ es}$ | [$MWh_{ex}$] | 18238.48 | 18050.65 | 18082.26 | 17967.31 | 21385.41 | 21314.91 | 18611.96 | 18391.7 |
| | Solar radiation, $E_{xtot\ sol}$ | [$MWh_{ex}$] | 74951.07 | 74951.07 | 80031.39 | 80031.39 | 100223.68 | 100223.68 | 73632.06 | 73632.06 |
| | Reusable waste, $E_{xtot\ rec}$ | [$MWh_{ex}$] | −6.2 | −8.53 | −3.96 | −5.34 | −3.25 | −4.2 | −7.12 | −9.3 |
| Life cycle exergy inflow | Non-renewable exergy feed, $F_{tot\ n\text{-}r}$ | [$MWh_{ex}$] | 18618.73 | 18414.57 | 19987.55 | 19905.75 | 23728.28 | 23669.43 | 18926.22 | 18728.07 |
| | Renewable exergy feed, $F_{tot\ r}$ | [$MWh_{ex}$] | 76394.58 | 76360.13 | 80274.6 | 80254.1 | 100478.97 | 100464.9 | 75064.9 | 75032.68 |
| Life cycle exergy outflow | Air emissions, $E_{xtot\ em}$ | [$MWh_{ex}$] | 107.08 | 102.82 | 65.28 | 62.68 | 62.77 | 57.86 | 114.12 | 110.13 |
| | Water emissions, $E_{xtot\ lw}$ | [$MWh_{ex}$] | 13.74 | 13.18 | 8.64 | 8.14 | 7.95 | 7.81 | 10.12 | 9.86 |
| | Underground emissions, $E_{xtot\ uw}$ | [$MWh_{ex}$] | 0.097 | 0.097 | 0.114 | 0.114 | 0.131 | 0.131 | 0.097 | 0.097 |
| | Water-bourne substances, $E_{xtot\ ts}$ | [$MWh_{ex}$] | 6.44 | 6.44 | 7.81 | 7.81 | 9.2 | 9.2 | 6.46 | 6.46 |
| | Solid waste, $E_{xtot\ sw}$ | [$MWh_{ex}$] | 5.25 | 5.25 | 2.21 | 2.22 | 1.5 | 1.5 | 5.18 | 5.18 |
| | Other waste, $E_{xtot\ rw}$ | [$MWh_{ex}$] | 75.75 | 75.75 | 34.89 | 34.89 | 29.94 | 29.94 | 53.44 | 53.44 |
| | Electricity output, $E_{xtot\ el}$ | [$MWh_{ex}$] | 9526.87 | 9526.87 | 12829.64 | 12829.36 | 16112.4 | 16112.4 | 9554.1 | 9554.1 |
| Life cycle irreversibility, $I_{tot}$ | | [$MWh_{ex}$] | 85278.1 | 85065.76 | 87313.59 | 87213.64 | 107983.36 | 107979.08 | 84247.6 | 84021.48 |
| Life cycle exergetic efficiency, $\eta_{exergetic}$ | | [%] | 10.03 | 10.05 | 12.8 | 12.82 | 12.97 | 12.93 | 10.16 | 10.19 |
| Exergetic eco-efficiency, $\eta_{eco}$ | | [%] | 36.25 | 36.52 | 42.41 | 42.52 | 43.83 | 43.78 | 35.98 | 36.23 |

efficiency and the growing renewable exergy feed lead to an increased exergetic eco-efficiency. For most of the examined PV cases, the recycling of half the aluminum consumed (Al 50 %) slightly increases the life cycle exergetic eco-efficiency of the PV system installed in the Nisyros.

ELCA results can be visualized in exergy flow (Sankey) diagrams (Schlueter and Thesseling 2009; Soufi et al. 2004). KC-65T and forward case scenarios represent the extremes of present and future technology in PV manufacturing. By comparing the Sankey diagrams of KC-65T case and those of forward case, assuming that consumed aluminum is not

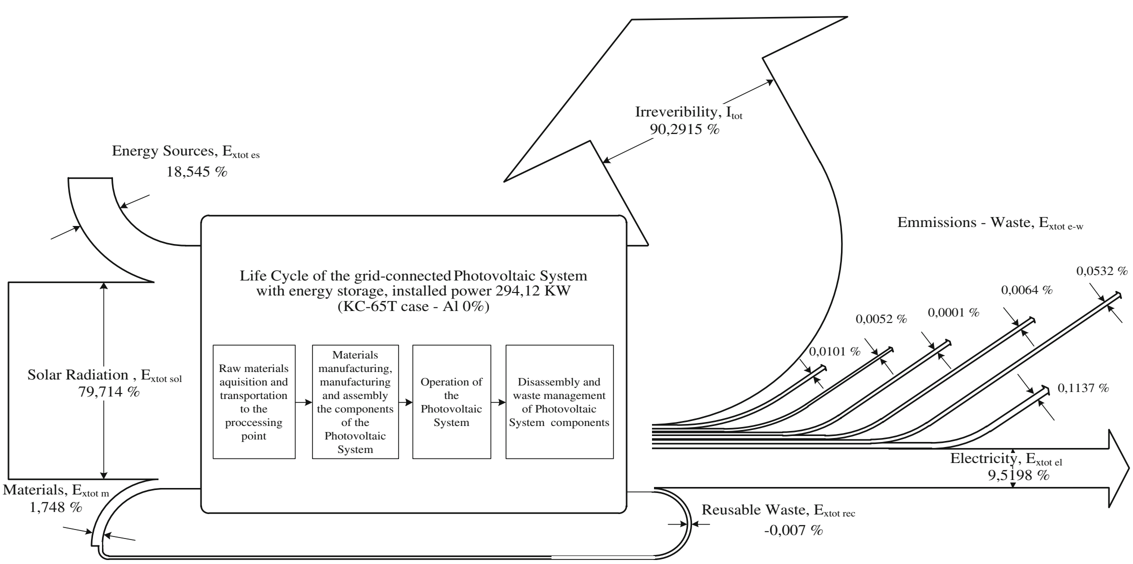


**Fig. 3** Sankey diagram for life cycle of the PV system. (KC-60 case - Al 0 %)

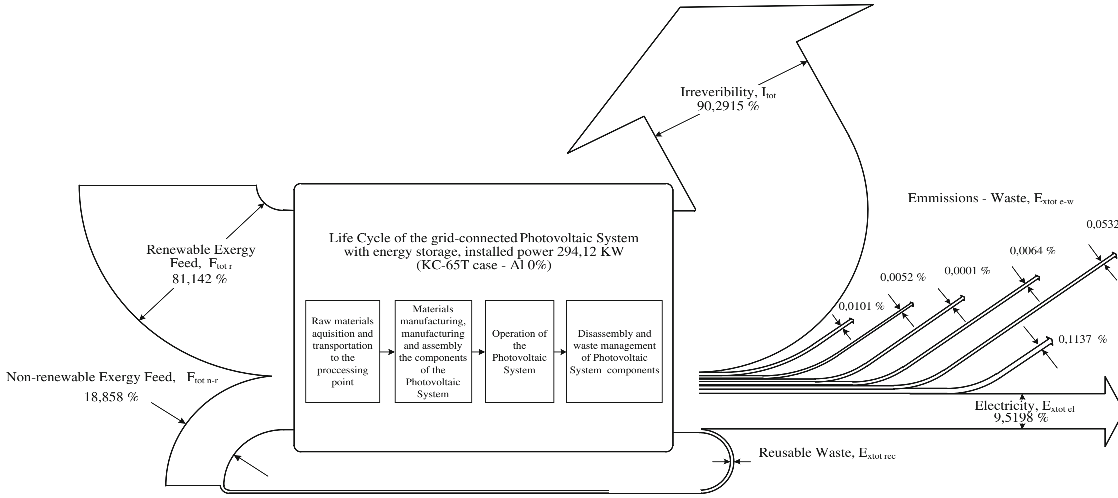


**Fig. 4** Sankey diagram for life cycle of the PV system, where the total exergy inflow is expressed in terms of non-renewable and renewable exergy feed (KC-60 case—Al 0 %)

recycled (Al 0 %), the technological progress in the field of PV systems can be soundly illustrated. The materials' exergetic contribution becomes greater. This increase is caused by the fact that the manufacturing processes of PV modules require larger quantities and materials with greater exergetic content. Moreover, the reusable waste exergy inflow is slightly decreased. Since, progress of PV technology requires high-purity materials, it is apparent that the amount of waste materials that can be reused is reduced. Moreover, due to the increased efficiency of the manufacturing processes of PV modules, the exergetic content of energy sources, emissions, and waste are slightly decreased. The more efficient utilization of the solar radiation by the panels of the PV system is proven by the solar radiation's increased exergetic contribution in the formation of the total exergy inflow. The solar radiation's exergy content is essential to the formation of the renewable exergy inflow. Thus, in the Sankey diagrams, where the incoming exergy of the PV system is expressed in terms of renewable and non-renewable incoming exergy, the renewable exergy inflow is found to be increased (Figs. 3, 4, 5, and 6).

## 6 Discussion

The evolvement of photovoltaic technology, especially in solar cell manufacturing, and the contribution of recycling have both been confirmed as part of an eco-friendly development in the present research. In specific, comparison of the

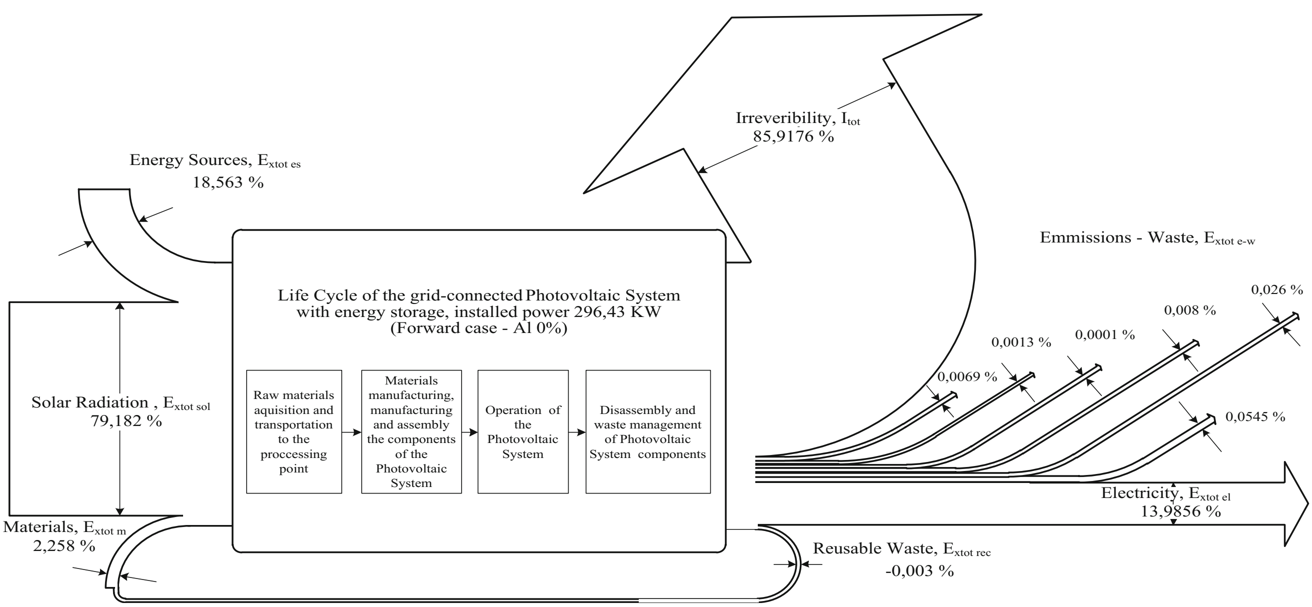


**Fig. 5** Sankey diagram for life cycle of the PV system (forward case—Al 50 %)

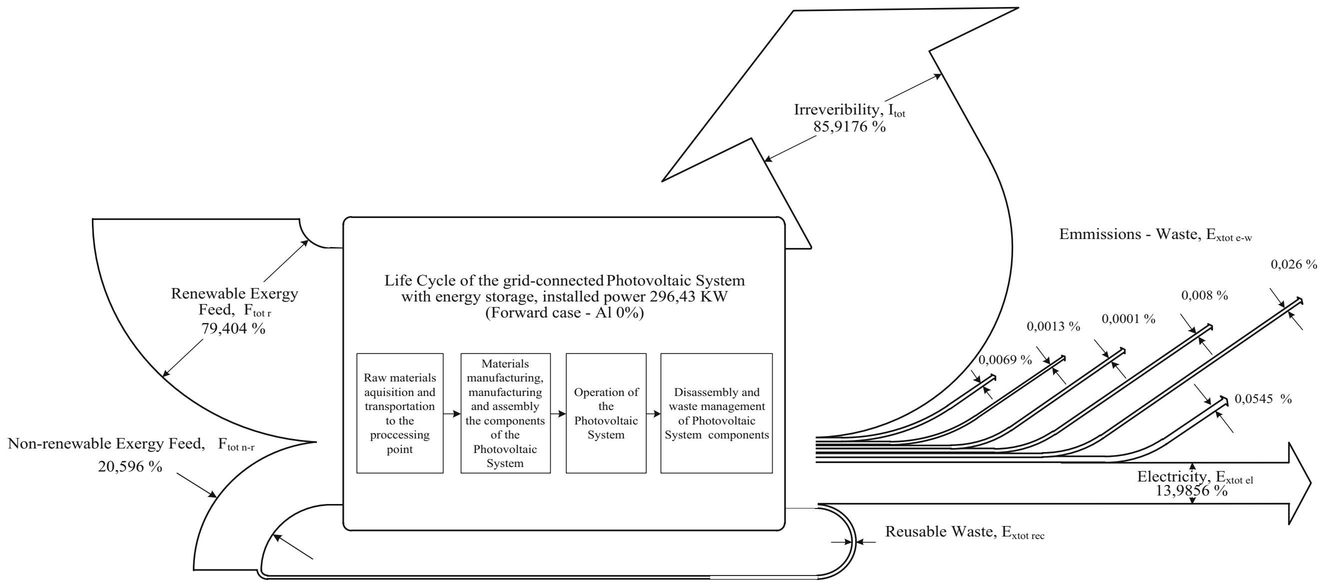


**Fig. 6** Sankey diagram for life cycle of the PV system, where the total exergy inflow is expressed in terms of Non-Renewable and Renewable Exergy Feed. (forward case—Al 0 %)

various photovoltaic scenarios through the Sankey diagrams clearly shows a considerable improvement of the whole exergetic life cycle, in respect to both exergy inflows and outflows, based on the anticipated development of technology in this industry. This result comes into agreement with relevant conclusions of various researchers in the field (Tiwari et al. 2009; Joshi and Tiwari 2007). Then, recycling has proved to be an important step for the improvement of the exergetic life cycle. Reduced life cycle irreversibility and reduced exergy content of some categories of air emissions, water emissions, and other waste are the benefits of recycling and reuse of aluminum. Furthermore, the expression of life cycle incoming exergy in terms of non-renewable and renewable exergy feed leads to a decreased non-renewable exergy contribution in case of recycling and reuse of aluminum (Al 50 %), due to less energy consumed during the whole recycling chain (Hoque et al. 2012). The latter conclusions have been well-reported in other research studies (Ignatenko et al. 2007; Amini et al. 2007; Castro et al. 2007). The non-renewable exergy feed reduction is caused by the fact that the aluminum recycling involves a reduced demand for virgin natural resources (von Gleich 2006).

The most important remark of the comparison between the Sankey diagrams of the KC-65T case and those of forward case (i.e., the two extremes) is the increase of the life cycle exergetic efficiency, which is concluded from the increased electricity output of the PV-system. Consequently, the increased exergetic efficiency involves decreased irreversibility (exergy losses) of the PV system's life cycle. These outcomes are in agreement with the evolution of technological advances in the area (Koroneos and Tsarouhis 2012; Tiwari et al. 2011; Raman and Tiwari 2009). Overall, the environmental burdens released to air, water, and soil follow a pattern of reduced values. This is true while comparing across PV system technological scenarios as well as between non-reuse and reuse of recycled aluminum scenarios, confirming previous studies (Koroneos et al. 2006b; Stylos and Koroneos 2014).

## 7 Conclusions

The progress in the field of PV technology is significant and is stipulated by the increased life cycle exergetic efficiency. The conducted ELCA study showed evidently that the total exergy inflow and the irreversibility of the PV system's life cycle (for all the PV cases) is important. However, due to the fact that the contribution of the renewable exergy (solar radiation) to the formation of the total incoming exergy of life cycle is significant, it emerges that the satisfaction of electric power needs with a PV system appears to be exergetic sustainable. Thus, power generation through PV systems is an eco-friendly process while implementing a cradle-to-grave approach. Application of ELCA in electricity production technologies exceeds the proven sustainable prospective of the PV systems; however, it aims to show the essence of the application of ELCA methodology in the environmental decision making process. ELCA can be seen as a useful tool for the support and formation of the environmental decision making that can illustrate the examined energy system or process in terms of exergetic sustainability.

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